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OPTIONS FOR THE DISPOSAL OF FORMATION FLUID BRINE BY OIL PRODUCERS IN PETROLIA, ONTARIO

AN ENVIRONMENTAL-ECONOMIC ASSESSMENT

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Ontario

Jim Bradley
Minister

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OPTIONS FOR THE DISPOSAL OF FORMATION FLUID BRINE BY OIL PRODUCERS IN PETROLIA, ONTARIO

AN ENVIRONMENTAL-ECONOMIC ASSESSMENT

Prepared for

The Southwest Regional Office
Ontario Ministry of the Environment

and

The Petroleum Resources Section
Ontario Ministry of Natural Resources
London, Ontario.

by

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TABLE OF CONTENTS

Page No.

LIST OF TABLES iii
LIST OF FIGURES iv
ABSTRACT. v
RESUME. vi
EXECUTIVE SUMMARY vii

1.0 INTRODUCTION
  1.1 Background. 1
  1.2 Study Objectives. 2
  1.3 Methodology 2
  1.4 The Plan of the Report. 3

2.0 OIL, BRINE AND THE ENVIRONMENT
  2.1 Oil Production from the Petrolia Oil Pool. 4
  2.2 Environmental Effects of Brine Discharges. 14

3.0 BRINE DISPOSAL - TECHNOLOGIES AND ECONOMICS
  3.1 Brine Disposal Options. 17
  3.2 Disposal Wells, the Preferred Option. 17
  3.3 Cost Estimates Used in Analyses . . 20
  3.4 Application of the Location-Allocation Model. 21

4.0 SENSITIVITY ANALYSES OF UNCERTAIN MODEL PARAMETERS
  4.1 Definition of Alternative Parameter Values. 28
  4.2 Results of Sensitivity Analyses . . 30

5.0 ECONOMIC IMPLICATIONS OF BRINE DISPOSAL COSTS
5.1 Financial Implications of a Disbursed System. 32
5.2 Financial Implications of Centralized Systems 33

6.0 CONCLUSIONS AND RECOMMENDATIONS
6.1 Conclusions 37
6.2 Recommendations 38

BIBLIOGRAPHY

APPENDIX A: LOCATION-ALLOCATION MODEL FOR EVALUATING THE COSTS OF BRINE WELL DISPOSAL OPTIONS

LIST OF TABLES

Page No.

2.1 Oil Production from Devonian Oil Pools in Southern Ontario. 7

2.2 Oil Producers and Operators in the Petrolia Oil Pool (MNR #12) as of January 6, 1986. 10

2.3 Petrolia Oil Pool Production and Revenues 11

2.4 Pollution Sources to Four Watercourses in the Petrolia Area 16

3.1 Brine Disposal Technologies and Options. 18

3.2 Summary of Default Values for Petrolia Oil Pool Used in the Location-Allocation Model 23

3.3 Comparison of Brine Disposal Facility Location and Transport Options 25

4.1 Summary of Results of Sensitivity Analysis 31

5.1 Annual Oil Production Costs of Devonian Producers in Petrolia, Ontario 35

A.1 Summary of Default Values for Petrolia Oil Pool Used in Location-Allocation Model

LIST OF FIGURES

Page No.

2.1 Annual and Cumulative Oil Production, 1863 - 1986 5

2.2 Town of Petrolia Showing Locations of Oil Producers and Transport Links Among Them 8

2.3 Prices for Petrolia Pool (#12) Crude 1985 12

2.4 Prices for Petrolia Pool (#12) Crude 1986 12

ABSTRACT

Oil wells in southwestern Ontario produce varying amounts of formation fluid consisting of a mildly salty water along with crude oil. After separation from the oil, this water component (called "brine") is discharged to holding ponds or directly into area watercourses.

Brine contain chlorides, hydrogen sulfides, ammonia and small amounts of residual hydrocarbons (e.g., heavy paraffin wax fractions) which can impair the quality of receiving waters.

Disposal of the brine into a porous geological formation below the oil bearing strata, the Detroit River Group, was determined to be the technically and environmentally preferred brine disposal method for the area. The costs of implementing different disposal program options using this technology were estimated by means of a location-allocation model.

The model was used to determine the least-cost transportation modes (truck or pipeline) and locations of disposal wells under different conditions and assumptions. Given available input data, the least-cost program included brine transport by pipeline to two centralized disposal operations at a total annual cost of $122,000. This cost amounts to 9% of the 1985 gross revenues for the Petrolia producers.

Sensitivity analyses showed that the cost of pipe installation, completing a disposal well and the cost of brine pumps can have the largest effect on transport costs and optimal disposal well locations.

Since oil producers have no experience with the installation or operation of pipelines to centralized disposal facilities, these cost estimates uncertain and likely overstated.

It is recommended that a demonstration project be established to test the installation and operation of a centralized disposal facility utilizing a pipeline. Over the longer term, a system of shared and private brine disposal facilities should be evolved at minimum cost. New oil wells should be approved only if acceptable brine disposal facilities are provided.

RÉSUMÉ

Les puits de pétrole du sud-ouest de l'Ontario produisent en quantité variable un fluide de formation composé d'une d'eau légèrement saline et d'huile brute. L'eau, ou saumure, est d'abord séparée de l'huile puis rejetée dans des étangs ou directement dans les cours d'eau de la région.

La saumure est composée de chlorures, d'hydrogène sulfuré, d'ammoniac et de petites quantités d'hydrocarbures résiduaires (des fractions lourdes de paraffine, par exemple). Toutes ces substances chimiques peuvent nuire à la qualité des eaux dans lesquelles elles sont déversées.

Il semblerait que la meilleure méthode d'élimination de la saumure dans cette région, au double plan technique et environnemental, soit de la rejeter dans la couche géologique poreuse située sous la strate pétrolifère, ou formation géologique, de la rivière Detroit. Pour évaluer le coût de mise en oeuvre des différentes méthodes d'élimination à partir de ces techniques, on s'est servi d'un modèle de localisation et de répartition.

On a utilisé ce modèle pour déterminer les modes de transport les moins coûteux (camions ou pipelines) et l'emplacement des puits de refoulement dans certaines conditions et selon diverses hypothèses. D'après les données recueillies, la méthode la moins coûteuse consisterait à transporter la saumure par pipeline jusqu'à deux puits de refoulement centraux. Le coût total par année de cette méthode est de 122 000 $, ce qui représente 9 % des revenus bruts des producteurs de la région de Petrolia en 1985.

Les analyses de sensibilité ont révélé que le coût d'installation des tuyaux et de construction d'un puits de refoulement ainsi que le prix des pompes influent largement sur les coûts du transport et sur le choix de l'emplacement idéal pour les puits de refoulement.

Compte tenu du fait que les producteurs de pétrole ont peu d'expérience de l'aménagement ou de l'exploitation de pipelines reliés à des installations de refoulement, ces chiffres sont hypothétiques et probablement exagérés.

Nous recommandons donc de mettre sur pied un projet-pilote afin d'évaluer l'aménagement et le fonctionnement d'un puits de refoulement central relié à un pipeline. Il faudrait à long terme créer un réseau de puits de refoulement, et individuels et partagés, au coût le plus bas possible. En outre, les nouveaux puits de pétrole ne devraient être autorisés que si les producteurs ont aménagé des puits de refoulement satisfaisants.

EXECUTIVE SUMMARY

1. Oil wells in Southwestern Ontario produce a mixture of oil and a slightly salty sulphurous water component called brine.

2. For many years, oil producers have discharged brine into area watercourses causing impairment of the water quality in the Stonehouse Drain and other area watercourses.

3. A program of gradual, but ultimately complete, elimination of brine discharges into area watercourses is, therefore, desireable.

4. Between 14 and 17 producers operate oil wells in the Petrolia Oil Field in south-western Ontario. These operators generated the following amounts of oil and revenues during 1984 and 1985:

Year	Oil Production (cubic metres)	Total Revenues $000's	Average Revenues $/M³
1984	6,276	1,200	191.20
1985	6,619	1,400	211.51

5. Oil production from the Petrolia field generates approximately 125,000 m³ of brine each year. This estimate is based on an estimated "average" brine-to-oil ratio of 20:1.

6. Based on research and an evaluation by Petrolia oil producers, the only environmentally acceptable disposal method, which is also technically feasible at this time, is to inject the brine into wells drilled to the porous Detroit River Group of rocks.

7. Brine disposal wells could be installed by each of the active Petrolia oil producers or one or two centralized facilities could be constructed with brine transported to them by pipeline or by truck.

8. A "location-allocation" model was developed to determine least-cost configurations of disposal wells and transport systems.

9. Using the location-allocation model with a specific set of initial input data, 5 different disposal options were postulated and examined. These include:

   a. Least-cost location(s) of centralized disposal well facilities and transportation modes among all (34) possible sites (nodes) in the Petrolia area.

   b. Least-cost system of central disposal facilities and transportation modes at existing (14) oil producer sites only.

   c. Locate centralized disposal facilities only at sites with existing disposal wells.

   d. Require only truck transport of brine to central disposal facilities.

   e. Construct disposal wells at each producer site.

10. Building disposal wells at each producer site would require a capital expenditure of about $60,000 per well.

11. Based on the location-allocation model, the least-cost brine disposal program would locate two central disposal facilities at the existing Bear Creek Resources (#3) and Jacques (#9) producer sites where disposal wells are already in place. Brine would be transported by pipeline for all but two producers. This program would cost all producers about $122,000 per year.

12. Using trucks to transport brine from all producers to centralized facilities, rather than a pipeline, would cost about 3.6 times as much as the least-cost centralized disposal program.

13. The aggregate, annual cost of the least-cost brine disposal option amounts to about 9% of total annual revenues in 1985 for all Petrolia producers. However, brine disposal costs vary substantially from one producer to another such that it will probably be less costly for some of the larger producers to install their own disposal wells rather than pay annual disposal fees.

14. Because of the uncertainties associated with many of the location-allocation model parameters, the results that were generated in this exercise likely overstate the actual costs of a brine disposal program.

15. A sensitivity analysis was carried out to determine least-cost disposal well locations among the 14 existing oil production sites with the associated transportation costs. Sites #2, #4, #7 and #9 were consistently identified as least-cost disposal sites under the various parameter values.

16. Each of the producers would experience reductions in their profits as a result of a brine disposal program. A few of the smaller producers could experience absolute losses (e.g., extra total costs could be greater than total revenues) if any of the disposal programs were adopted.

17. In the short term, a central disposal facility demonstration project should be established involving two to four producers. This project would provide experience in designing and operating a communal facility and an inter-producer pipe system.

18. A longer-term program for brine disposal can be specified, contingent upon the results of the research/demonstration project.

1.0 INTRODUCTION

1.1 Background

Oil deposits in southwestern Ontario have been tapped since the beginning of the North American oil industry. Oil pools that are located beneath Oil Springs and Petrolia, Ontario were discovered in 1858 and 1862 respectively (Habib and Trevail, 1984: 22). These pools may well have the longest continuous record of production on the continent. Indeed, the names Oil Springs and Petrolia evoke the heritage that oil holds for the people of the region. While the major petro-chemical complex at Sarnia, Ontario owes its existence to the early development of oil production in the area, the petroleum industry has long outgrown its origins in and around Petrolia and Oil Springs.

Oil wells in southwestern Ontario produce varying mixtures of crude and brine which are called "formation fluids". The brine, with a concentration of about 10,000 ppm NaCl and a specific gravity of approximately 1.02 is about one-third as salty as sea water. Oil brine, which is not the same as a saturated solution of sodium chloride, often contains odorous hydrogen sulfide, ammonia and small amounts of residual hydrocarbons, particularly heavy paraffin wax fractions.

The oil-brine formation fluid is pumped to the surface where it is separated by gravity in tanks. Crude oil floats to the top while the brine is drained into holding ponds or, in some instances, discharged directly into area watercourses. The oil is collected by truck and taken to a "bulk plant" in Sarnia owned by the shipper. From this bulk plant, the oil is pumped directly to the Imperial Oil refinery in Sarnia.

In the early years, so much oil was discharged with brine that oil skimming from ponds and watercourses was profitable (Wood, undated). Now, however, the oil-brine separation is virtually complete, although the residual brine still contains hydrogen sulphide and other contaminants noted above.

Even though cattle reputedly drink the brine fluids without ill-effect, bio-chemical surveys of watercourses in and around Petrolia during 1976, 1979 and 1981 have shown that water quality has been seriously impaired in certain streams and that brine discharges are, in some cases, responsible for violations of provincial water quality criteria (Wood, undated). In addition, people in the area have complained about sulphurous odours in stream beds.

The Ministry of the Environment advised Petrolia area oil producers in 1984 that environmentally acceptable methods of brine disposal would have to be adopted and that the practice of discharging brine into streams would have to come to an end. Consequently, the Ministry of the Environment, together with the Ministry of Natural Resources (MNR), undertook to identify and evaluate options for curtailing brine discharges into streams. The Ministry of Natural Resources is involved because it is responsible for regulating oil exploration, well drilling, oil production and the subsurface disposal of oil production by-products.

Oil production operations are deemed to be part of the heritage of these communities and of Ontario. Indeed, the land on which many of the small producers operate have been owned by the producers' families for generations. This historical aspect of the operations gives impetus to the need to carefully design brine disposal programs that will avoid undue economic disruptions and closures.

1.2 Study Objectives

Recognizing the potential economic dislocations to oil producers that could result from a major program to remove oil well brine from local watercourses, a study was commissioned to:

- identify methods, systems, technologies and options for, and estimate costs of, the disposal of brine from producing oil wells in the Petrolia oil field;
- determine the economic implications of the extra costs of brine disposal, particularly as they affect oil producers in the Petrolia oil pool;
- provide recommendations regarding the elements of, and a timetable for, implementing an abatement program for brine disposal;
- comment on other implications that may be revealed.

1.3 Methodology

In the course of this investigation, a procedure was developed to evaluate different disposal options and identify the least-cost brine transport and disposal systems. The procedure, a "location-allocation model", was used to compute the number and arrangement of brine disposal facilities which would minimize the sum of transportation, operation and construction costs, given specific assumptions and input data. The model was applied to those producers who operate wells in the Petrolia pool in order to generate cost estimates that can be used to assess the possible economic consequences of a brine disposal program.

The location-allocation model could also be applied to other oil fields and input data which are uncertain can be modified to perform sensitivity tests.

1.4 The Plan of the Report

In Chapter 2, the physical dimensions of the petroleum industry in Petrolia and the pollution problems casued by brine are described. The focus of the discussion is the Petrolia Oil Pool and its operating producers. Oil production systems are described, while relevant biophysical and economic data are assembled and interpreted.

Elements of a brine disposal system are described in Chapter 3. The preferred system involves injection of residual fluids via specially designed disposal wells into the Detroit River Group of Formations. Results of a location-allocation optimization procedure are presented. These results include estimates of the costs of several system designs.

A sensitivity analysis is presented in Chapter 4. In this analysis, the most uncertain variables are systematically raised or lowered and the results of the empirical model applications are compared.

In Chapter 5, the economic implications of possible disposal programs on Petrolia area producers are discussed. Comments about the potential benefits of the programs are also presented.

Finally, implications and recommendations for a brine disposal program are presented in Chapter 6.

A detailed description of the location-allocation optimization procedure is found in Appendix A.

2.0 OIL, BRINE AND THE ENVIRONMENT

2.1 Oil Production from the Petrolia Oil Pool

Commercial oil production from deposits in southwestern Ontario has been recorded since 1863. Figure 2.1 shows annual and cumulative production from 1863 through 1982. Annual petroleum production from all of Ontario peaked in 1966, totalling 210,464.0 cubic meters (m^3) or about 1,323,800 imperial barrels (Habib and Trevail, 1984: 20).[1] Figure 2.1 shows that oil production in Ontario has declined steadily since 1966 until 1982 when the trend was reversed. Total oil production in 1984 amounted to 90,344 m^3 and it reached 135,816 m^3 in 1986 (Trevail, 1987). In 1982, total Ontario oil production amounted to 85,637 m^3 or 538,656.7 imperial barrels.

The Imperial Oil Ltd. (IOL) refinery in Sarnia, where all of the petroleum produced in Ontario is processed, has a daily capacity of 21,500 m^3 per day or about 7 million m^3 per year. Total oil production from all of Ontario's oil wells during 1982 amounted to 85,637 m^3 per year or only 1.2% of the annual capacity of this one refinery.

The oil produced from Petrolia and other nearby oil fields is collected by trucks operated by Harold Marcus Ltd. of Sarnia. The oil is delivered to a bulk plant owned by Marcus. From the bulk plant, the oil is then pumped directly to the Imperial Oil refinery as it is needed.

Hydrocarbon deposits (oil and gas) are entrapped in each of the four major geological units found in southwestern Ontario: the Devonian, Silurian, Ordovician and Cambrian. About 39% of the total annual Ontario oil production in 1983 came from Devonian age deposits (Habib and Trevail, 1984: 22). Devonian petroleum deposits are relatively shallow, ranging from 30 to 160 metres (90 to 480 feet) in depth. Silurian age oil pools, which account for another 41% of Ontario's annual oil production, are found at depths of 300 to 800 metres or 900 to 2,400 feet (Habib and Trevail, 1984: 22-23).

Since 1858, twenty-five oil pools or fields have been discovered in the Devonian age formations of southern Ontario (Bailey Geological Services, Ltd., 1985: 77). Only seven of these pools are still in production, although five have accounted for 98.6% of the total cumulative oil production from the Devonian formations. Three of the seven active pools - Petrolia, Oil Springs and Rodney - account for more

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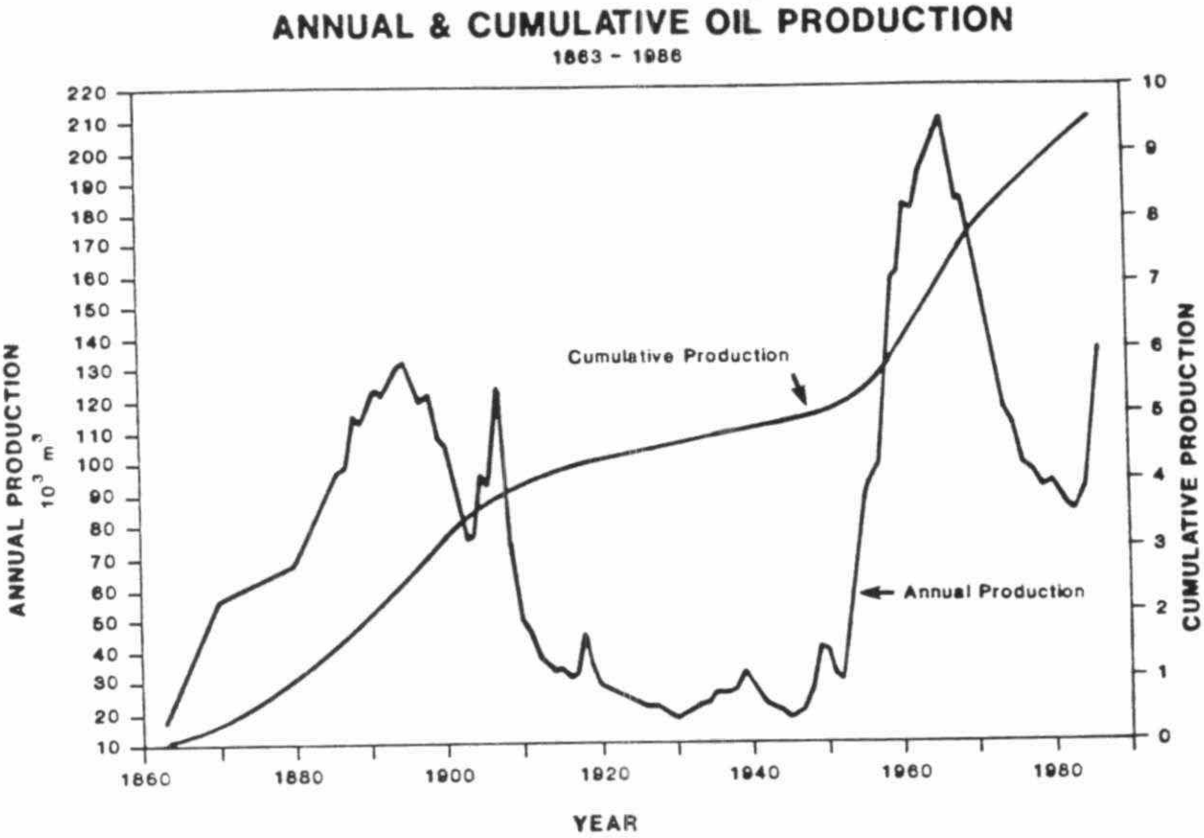
[1] One cubic metre, (m^3) = 6.29 imperial barrels.

FIGURE 2.1



SOURCE: Petroleum Resources Section, Ontario Ministry of Natural Resources, London, Ont.

than 88% of the oil taken from Devonian strata. The distribution of production from major Devonian pools, as of December 31, 1981, is shown in Table 2.1.

The focus of the present study is the Devonian age Petrolia Oil Pool. Oil is also produced from a deeper Silurian deposit, called the Petrolia East Pool, in the Petrolia area. In 1982, six wells were being operated by Ram Petroleum which were drilled to depths of between 580 to 625 metres and which produced 2,279.1 m^3 of oil (Habib and Trevail, 1984: 2). Because brine is not associated with oil produced from these wells, they are not addressed in this study.

Oil production from the Petrolia pool has varied substantially from year to year. Since 1978, production has been rising in response to higher prices for oil, with new wells being drilled and old wells being brought back into production. Total production in the Petrolia field rose from 3,322 m^3 in 1978 to 6,619 m^3 in 1985. The field now accounts for almost 10% of Ontario oil production.

Despite the drop in oil prices during 1986, the Petrolia pool is likely to see continued increases in the numbers of producers, wells and production. This continued growth in output may be explained in part by the fact that recent lower oil prices are still substantially higher than oil prices that prevailed prior to 1973.

Depletion of the pool is not, however, a factor over the time horizon relevant to this investigation.

For the purposes of this study, it is necessary to define the limits of the Petrolia pool, designated Field No. 12 by the Ministry of Natural Resources (MNR). Although the explored and confirmed area of the pool extends well beyond the limits of Enniskillen Township, the current area of production is much smaller. Active producers are located in the area of Enniskillen Township in Concession (Con.) 13, Lots 8 and 9; Con. 12, Lots 9 through 12; Con. 11, Lots 12 through 15; Con. 10, Lots 14 through 17 and Con. 9, Lots 13 through 15. A map of the Petrolia area showing the producing well locations is presented in Figure 2.2.

TABLE 2.1

Oil Production from Devonian Oil Pools in Southern Ontario

Source/Pool	Annual Output for 1982		Cumulative Production as of Dec. 31, 1981	
	(m³)	(%)	(m³)	(%)
Total for Ontario	85,637.3	-	9,149,624.1*	
Total for Devonian Pools	33,753.5	100.0	6,373,680.5	100.0
Petrolia	5,445.4	16.1	2,760,287.0	43.31
Oil Springs	5,660.3	16.8	1,478,815.0	23.20
Rodney	20,788.5	61.2	1,375,092.0	21.51
Bothwell-Thamesville	1,520.6	4.5	498,414.0	7.82
Glencoe	293.5	0.9	171,841.0	2.70
Sub-total	33,708.3	99.5	6,284,449.0	98.54

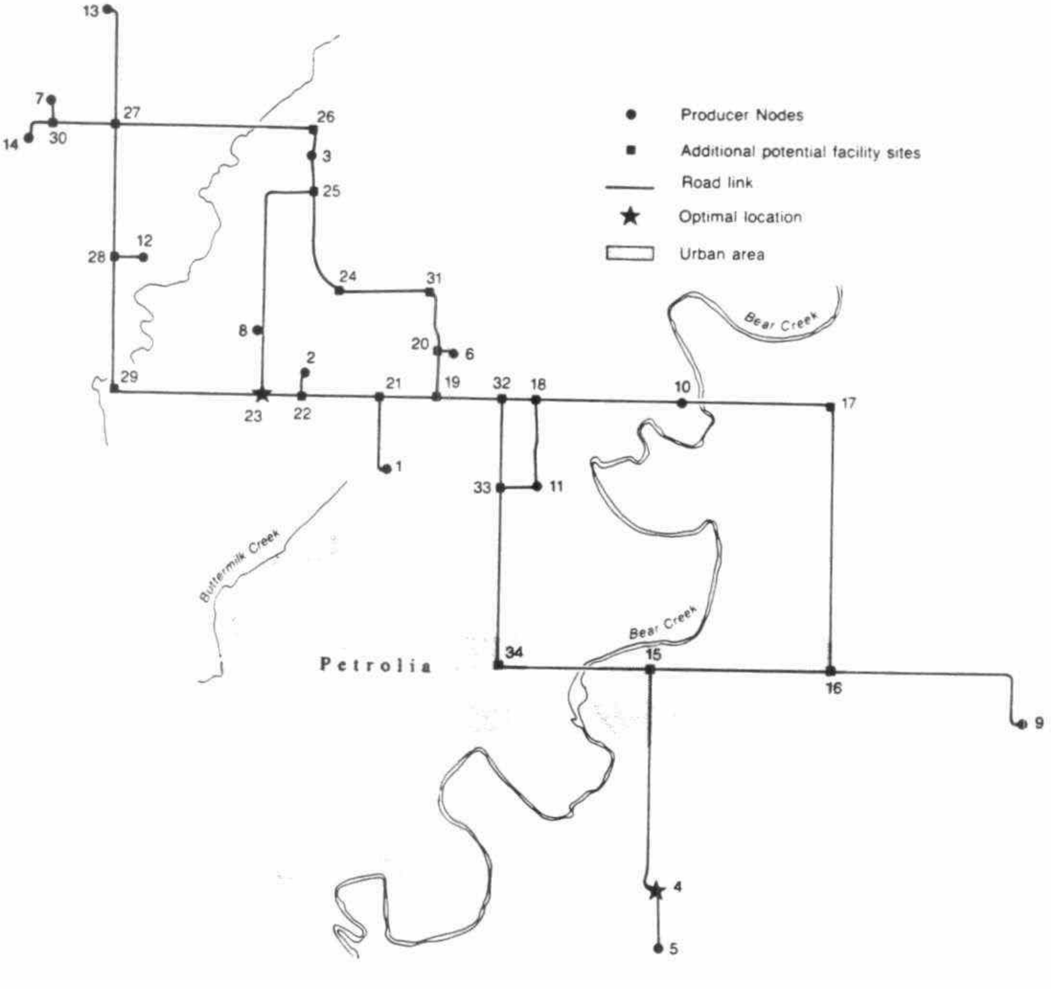
*As of December 31, 1982

Sources:

Annual output: Habib, A.E. and Trevail, R.A. (1984: 20,22).

Cumulative Production: Bailey Geological Services Ltd. and Robert O. Cochrane. (1985: 45).

FIGURE 2.2
TOWN OF PETROLIA SHOWING LOCATIONS OF OIL PRODUCERS, TRANSPORT LINKS AND OPTIMAL DISPOSAL SITES



Optimal disposal site locations are based on Default Values for model parameters.

Two key sources of oil production data were examined in the course of this study:

(a) Imperial Oil Limited's refinery records of oil deliveries and payments; and

(b) Ministry of Natural Resources Form 108, which gives lot and concession locations of producers.

In some cases, the number of wells being operated and the amount of brine being produced are provided on these forms.

The IOL refinery records identify producers who ship crude oil to the refinery. Table 2.2 lists the 17 Petrolia producers which sold oil to the IOL refinery in 1985. Concession and Lot numbers indicating the location of the producers, and the number of active wells operated by each, are shown in Table 2.2 as well.

In 1984, a total of 6,276 m^3 were produced. In 1985, the 17 producers listed in Table 2 produced a total of 6,619 m^3. At an overall price of \$191.89 per m^3, total revenue for producers was \$1.2 million in 1984. Total revenue for 1985 amounted to \$1.4 million. The average price during 1985 was \$216 per m^3, slightly higher than during 1984. These data are summarized in Table 2.3.

Of the 17 producers, five can be considered "large", producing over 500 m^3 of oil per year. These large producers operate 10 or more wells. Revenues for the five largest producers during 1985, which accounted for 66% of total revenues in that year, ranged from \$145,000 to \$250,000 per producer.

Prices for crude from Petrolia and from other Ontario oil pools are set by Imperial Oil and are based on world reference prices. Prices paid for Petrolia crude are graphed for 1985 and 1986 in Figures 2.3 and 2.4. These graphs show that the price of Petrolia crude remained at \$191.89/m^3 between January 1, 1983 and June 1, 1985. The price then rose to \$236.80/m^3 during the summer of 1985, but then fell slightly to \$229.32/m^3 by the fall of 1985. Oil prices fell precipitously in 1986, following the decline in world oil prices. By September 1986, prices had fallen to \$118.57/m^3 (about \$18.85 per barrel).

TABLE 2.2

Oil Producers and Operators in the Petrolia Oil Field (MNR #12) as of January 6, 1986

No.	Operator/Address	MNR #	Imp. Oil Prod. No.	Tender No.	Property Location/ Description Con.	Lot	Number of Operating Wells (1984)
1	Mr. Roy Ayrheart Blind Line P.O. Box 595 Petrolia, Ont. NON 1R0	048	116	T.448	11	12 (Kells Property)	4
2	Orval & Irene Ayrheart P.O. Box 595 Petrolia, Ont. NON 1R0	044	110	T.299	12	11 (E½)	12
3	Bear Creek Resources Ltd. c/o Mr. S. Gavreau-ABC Managers Ltd. 2 Thorncliffe Park Drive Unit 51 Toronto, Ontario M4H 1H2	008	139	T.446 A.553	12 12	11 12	11 15
4	Harold Bender 184 Adelaide St. Strathroy, Ontario N7G 2V5	007	122	A.001 T.550	10 9 12	14) 14) 15 A&B Range Well #2	12 1
5	Walter Brand P.O. Box 1108 Petrolia, Ontario NON 1R0	051	135	T.300	9	14 (Copeland Prop.)	11
6	Canflow Services 373 South Vidal Street Suite A Sarnia, Ontario N7T 2V3	130	146	T.606 T.603	12 12	12 Enniskillen 12 (E ½ Lot)	-
7	Cartier Resources Inc. 111 Richmond Street W. Toronto, Ontario M5H 2G4	056	149	A.540	13 12	8, 9 7	4
8	Mrs. Ruth A. Edward P.O. Box 125 Petrolia, Ontario NON 1R0	068	183	T.502	12	11 (Edward Property)	24
9	Mr. Willis N. Jacques 4075 Petrolia Street P.O. Box 778 Petolia, Ontario NON 1R0	078	261	T.271	10	17 (Jacques Enniskillen)	18
10	William G. Noble General Delivery Oil City, Ontario NON 1R0	133	365	T.619	12	14,15	?
11	Petrolia Discovery Foundation Inc. P.O. Box 1480 Petrolia, Ontario NON 1R0	001	417	T.508	11	13 (Bradley Property)	9
12	Mrs. Dorothy Stevenson P.O. Box 91 Petrolia, Ontario NON 1R0	110	465	-	12	10	21
13	Frank Vye R.R. #1 Brigden, Ontario NON 1B0	-	540	T.575	13	9	-
14	Gordon Williams P.O. Box 298 Corunna, Ontario NON 1G0	-	547	A.562	12	9	6
15	Murray Bradley 4422 North Street Petrolia, Ontario NON 1R0	-	121	T.661	Bradley Property Noble Well		-
16	Lyons Wilson & Baines P.O. Box 1138 Petrolia, Ontario NON 1R0	-	167	T.654	Petrolia Well		-
17	625138 Ontario Limited c/o Mr. Owen Gray P.O. Box 903, Sarnia, Ontario N7T 7J9	-	347	T.651	Tank Street Well		-

Source: "Ontario Crude System - Master List", Imperial Oil Co., Jan. 6, 1986

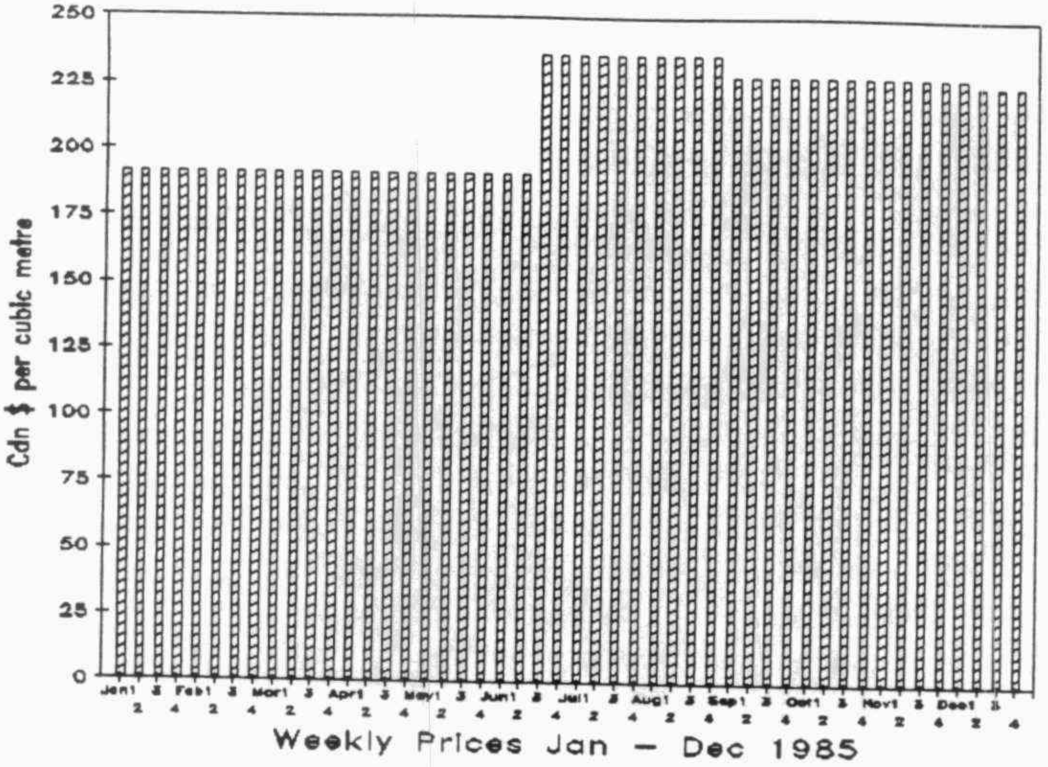
TABLE 2.3

Petrolia Oil Field Production and Revenues

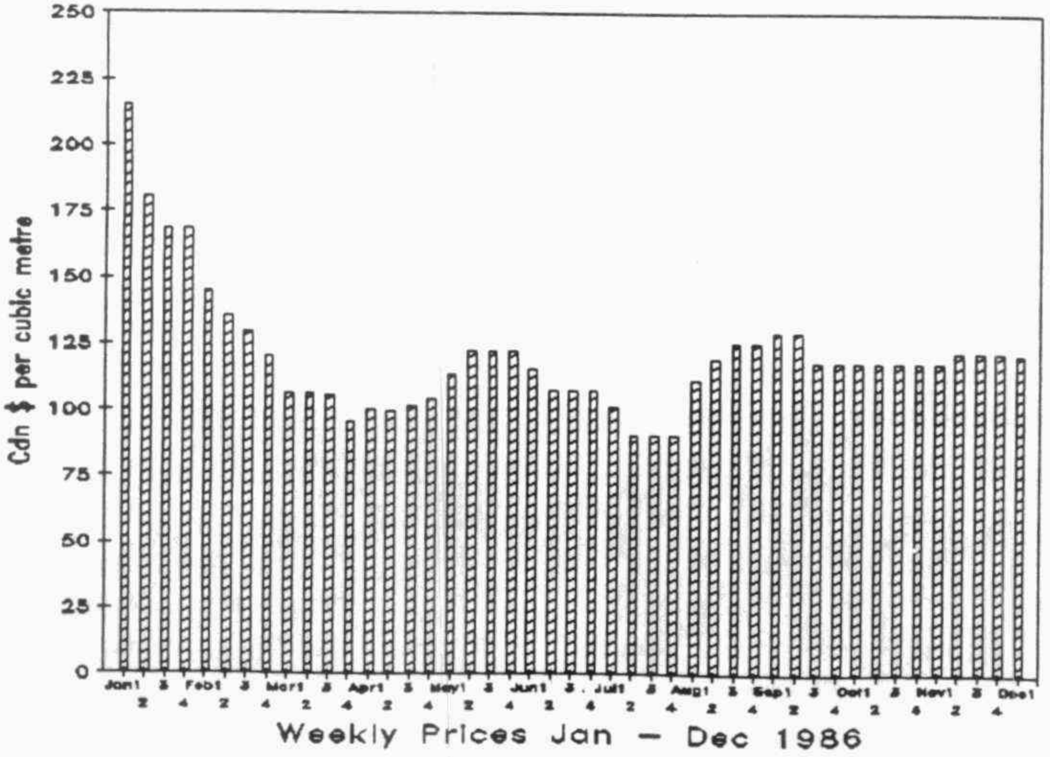
	1984	1985
Total number of producers	17	17
Total Oil Production (m^3)	6,276	6,617
Total Revenue ($M)	$1.2	$1.4
Number of Producers used in Location-Allocation Model	14	14
Total Oil Production for 14 producers	1.1	1.3

Source: Imperial Oil Ltd.

Prices for Petrolia Field (#12) Crude 1985



Prices for Petrolia Field (#12) Crude 1986



Even though crude oil prices are substantially lower than the high levels enjoyed during the early 1980's, current prices of $18-$19 per barrel are still substantially higher than the $5-$8 per barrel that prevailed prior to 1973. Although production costs are also higher, oil extraction from the Petrolia and other Devonian pools continues to be an attractive venture to many people.

Larger producers generally hire one or two full-time employees. One producer estimated that oil producers in Petrolia employ between 20 and 30 people full-time.

One operator, Petrolia Discovery Foundation, is a municipally-sponsored, non-profit organization. Buildings and pumping equipment used in this operation are over 100 years old. It is set up as a museum and revenues from visitors are reported to account for approximately 20% of the Foundation's total revenue.

Oil recovery operations from the wells in Petrolia are characteristic of most of the other pools in southwestern Ontario. Because thousands of wells have been drilled into various hydrocarbon formations over the past 125 years, gas pressure has dissipated. Therefore, in order to extract oil, a well is sunk to the oil-bearing strata. The oil-brine formation fluid seeps into the bottom of the shaft and this mixture is then pumped to the surface. The brine actually facilitates oil production because the oil-brine suspension flows into the wells much faster, and can be pumped more easily, than would the highly viscous crude oil by itself.

The ratio of brine to oil varies substantially from well to well and between operators. Figures given by operators on two MNR 108 forms are equivalent to 40:1 and 100:1 brine to oil ratios. Reported brine flow rates of four operators indicated ratios of 15:1, 35:1, 40:1 and 20:1. Verbal reports of 100:1 and 12:1 were given to the authors by operators during this study. Consequently, a 20:1 brine-to-oil ratio was judged to be a reasonable "average" figure for estimating brine production and the costs of disposal.

Using the 1984 oil production figures of 6,276 m^3, the 20:1 ratio yields an estimate of total brine production from the Petrolia field of about 125,500 m^3 per year. Actual brine production could be higher or lower but field surveys would be needed to determine a more reliable estimate.

2.2 Environmental Effects of Brine Discharges

A systematic assessment of the environmental damages and effects caused by each brine source would be helpful in designing a disposal program and in setting compliance schedules.

An assessment of environmental damages involves:

(1) an identification and quantification of brine discharges;

(2) a determination of the ecological effects of brine, including changes in ambient quality parameters; and

(3) an assessment of the significance of the ecological effects on people.

Table 2.4 presents a summary of pollution sources, including oil wells, on Bear Creek, Durham Creek, Buttermilk Creek and Stonehouse Drain. In addition to oil production brine, the Petrolia sewage treatment plant, storm drainage, agricultural drains and a poultry farm have been identified as pollution sources to Bear Creek. As indicated earlier, formation fluids are a source of excessive chlorides, hydrogen sulphides, ammonia and small amounts of oil globules, all of which can impair the water quality of the four water-courses noted in Table 2.4.

Water pollution may affect people directly if pathogens cause disease and illness. However, most adverse effects of water pollution in people occur as a result of environmental or ecological changes which, in turn, cause damages or discomfort to people. Some adverse ecological effects may not have any discernable impacts on human well-being.

Wood (undated), writing in 1980-81, notes that chloride levels in the Stonehouse Drain reached 3,300 mg/L, water was very turbid and that discharges of brine water and oil wastes severely impaired sections of the Drain (Wood, p.18). "One area resident has stated that at times the water in the drains kills his grass" (Wood, p.20).

Wood (p.18) also noted that "oil well odours" had been common in the Petrolia area. These odours have been markedly reduced during the past several years as some operators installed holding ponds and disposal wells. Hydrogen sulphides and mercaptans are able to evaporate before they entered the stream or water courses.

As noted, Bear Creek Resources installed a disposal well and discharges all of its brine into this facility rather than Buttermilk Creek. During the period of this study, three other producers installed disposal wells. These are Willis Jacques (#9), Canflow Services (#6) and Cartier Resource Inc. (#7). The Canflow disposal well was originally used to dispose of chemical wastes from Sarnia before this practice was banned in the middle 70's. Jacques, Bear Creek and Cartier installed their wells in order to expand the number of producing wells.

Nevertheless, oil field brine continues to degrade water quality in the Stonehouse Drain and other area water courses. Further reductions in oil field brine discharges to surface watercourses are, therefore, desirable until the practice ceases completely.

TABLE 2.4

Pollution Sources to Four Watercourses in the Petrolia Area

Watercourse	Producer	Brine Discharges (L/day)	Treatment Activity/Notes	Other Potential Sources of Pollution
Stonehouse Drain	1. Bear Creek Resources	40,000	Lagoons	1. Farm drainage 2. Storm drains 3. Septic tanks
	2. Orval Ayrheart	60,000	Shallow pond	
	3. Edward Estate	90,000	Lagoons (op. by O. Ayrheart) - oxidize H_2S - separate residual oil - precip. sulphides	
Buttermilk Creek	1. Bear Creek Resources		Disposal well installed	
	2. R. Ayrheart	4,500		
Durham Creek	1. Walter Brand	20,000	Brine is discharged onto land and does not reach creek as surface runoff	
Bear Creek	1. Petrolia Discovery Foundation		Aerated lagoon	1. Poultry operation 2. Petrolia Sewage Treatment Plant 3. Storm drainage 4. Septic tanks N.B. Below Petrolia, Bear Creek ultimately receives brine from most producers.
	2. P & E Oil Recyclers (Canflo Res.)	40,000		

Source: T.E. Wood (undated). "An Assessment of the Import of Devonian Oil Production in the Environment in the Petrolia Area". (Unpublished manuscript).

3.0 BRINE DISPOSAL - TECHNOLOGIES AND ECONOMICS

3.1 Brine Disposal Options

Five technical brine disposal or reduction methods have been identified and evaluated by a committee composed of Petrolia oil producers. The five methods and the results of the oil producers' investigations are summarized in Table 3.1

On the basis of technical feasibility and gross costs, deep well disposal of brine to the porous Detroit River Group rock stratum emerged as the preferred method. For this reason, the Ministry of the Environment and the Ministry of Natural Resources commissioned a study by Underground Resource Management, Inc. (1984) to investigate the environmental implications of deep-well disposal of brine into the porous Detroit River Group.

3.2 Disposal Wells, The Preferred Option

To inject brine fluids into the Detroit River Group, a well in the Petrolia area must be drilled to between 200 and 230 metres (600 - 700 feet). The well must then be cased through the shallower oil-producing zone to prevent leakage of brine back into the oil formation. In addition, design precautions must be taken to prevent corrosion since the sulphurous brine solution can become highly corrosive when exposed to air.

An entirely new disposal well may be drilled or an existing oil well may be drilled to the desired level, cleaned out, refurbished and converted into a disposal well.

Under current provincial Regulations (as administered by the Ministry of Natural Resources), all formation brines generated from new oil wells must be disposed of in an environmentally acceptable manner such as deep well disposal. Moreover, under provincial guidelines, the brine cannot be injected under pressure, but rather by gravity flow. As stated earlier, at least four Petrolia producers have installed disposal wells.

In order to obtain permits to drill 12 new oil wells, Bear Creek Resources was obliged to install a disposal well in 1983. A new well was drilled, completed and is presently operating.

One other operator, Willis Jacques, has deepened and refurbished an existing oil well into a disposal well in order to open new oil wells. Canflow Services in Petrolia has two chemical waste disposal wells. Only one of these wells is being used for brine disposal at this time. Finally, as noted, Cartier Resources has also installed a disposal well.

TABLE 3.1

Brine Disposal Technologies and Options

1. Reduction of Brine production by setting packers in oil wells.

   Pipe and cement casing is installed down to the bottom of the well. Casing is selectively perforated at precise depths, limiting the amount of water which can enter the well. Based on experiments, the Committee concluded that this method would not achieve a sufficient reduction in brine production.

2. Evaporation from Unlined Settling Ponds

   Brine would evaporate during the summer. However, sufficient capacity would be required to allow controlled discharge during periods of high natural runoff. This option was rejected because of likely odours, leakage to groundwater and difficulties in controlling discharges.

3. Salt Removal by Reverse Osmosis

   Reverse osmosis would remove, at most, 50% of the salts from the brine. This technology was rejected because it was virtually untested for this application and would likely be prohibitively expensive.

4. Aeration of Brine

   Aeration of brine hastens the oxidation of sulphurous compounds, thus reducing odours. However, it would leave brine volumes and concentrations largely unaffected.

5. Disposal via New or Existing Wells

   Brine fluids would be injected by gravity feed into the porous Detroit River Group which is deeper than the oil-bearing layers. Disposal wells were preferred on the basis of technical reliability and low cost.

Source: "Report of the Petrolia Oil Producers' Investigation Committee" (undated).

Producers in Petrolia who have installed disposal wells have reported that the total cost of drilling and completing each well was between $50,000 and $75,000 in current dollar values. The higher figure results from using all new equipment and salaried labour. Costs can be reduced by employing used equipment and pipe and by owner-operators doing the work themselves.

Unfortunately, it is not certain that a well drilled for disposal purposes will be successful because the permeability of the Detroit River Group is highly variable over short distances. Robert Cochrane, a petroleum engineer familiar with the area, estimated that a disposal well in the Petrolia area will have an 80% probability that it will be capable of accepting the desired flow of brine under the conditions imposed by the Ministries of Natural Resources and the Environment. This means that, for the facility to be operated continuously, at least one backup well will have to be drilled.

On the other hand, disposal installation well costs can be kept low through careful design features. In some situations, an unusable disposal well may be converted to oil production. Even if abandonment is necessary, the cost of casing and finishing the well need not be fully incurred. For those reasons, $60,000 will be used to estimate the average capital cost of installing a successful disposal well. This cost does not include any associated separation, retention or aeration facilities.

While the cost of a disposal well may be depreciated over five years, it is not yet clear just how long a brine disposal well will last physically. An official of Bear Creek Resources reported that parts of the well are experiencing corrosion problems after 2½ years of operation (J. Gauvreau, 1985).

In addition to corrosion, the brine fluids contain silt and other debris which may eventually clog the permeability of the porous disposal formation through which the fluid must disperse. Clogging can be avoided by filtration and settling of brine prior to injection. Otherwise lengthy, expensive and uncertain treatment procedures are required to unclog the formation. Therefore, the operating life of a disposal well may be no more than three or four years. If this is the case, more operating experience should be acquired before the installation of a large number of such wells.

Disposal options involving disposal wells can be organized along two dimensions. The first dimension concerns the number of disposal well facilities in the system. A fully centralized service would have one central facility for the disposal of brine from all producers. A completely decentralized service would require disposal wells to be installed by each operator. The centralized option would minimize total facility installation costs, but maximize transport costs. A decentralized approach would likely involve lower transport costs, but each producer would have to incur installation costs.

The second dimension concerns transport methods or modes. At one extreme is a system in which all of the brine moves by a pipeline from each producer to a disposal facility, with the other extreme having all brine trucked.

The lowest cost solution will likely be some point between the two extremes of each dimension.

3.3 Cost Estimates Used in Analyses

Disposal wells have an upper limit to the flow that can be accepted and dispersed continuously over an extended period of time. The Willis Jacques disposal well is reported to have easily absorbed the equivalent of an annual brine production of 40,000 m^3, while the Bear Creek well has been tested at the equivalent of 440,000 m^3, but only for a short period.

Until better data are available, the long term capacity of a "standard" disposal well will be assumed to be 300 m^3/day or 109,500 m^3/year of brine. At a ratio of 20:1, this is equivalent to an oil production of roughly 5,500 m^3/year, about 1,000 m^3 lower than current oil production.

It is assumed that a centralized disposal facility would consist of two disposal wells. This would ensure continuous operation and prevent the discharge of brine onto land or into area watercourses when one well is out of commission.

According to provincial regulations made under the Petroleum Resource Act, brine storage tanks must be above ground. Because the freezing point of oilfield brine is not much lower than that of water, brine storage tanks must be insulated for use during the winter. Pipes installed to carry brine to central facilities will likely have to be buried in order to protect against freezing and damage from vehicles. Costs of a pipeline, therefore, have to include trenching, as well as the necessary easements.

Based on discussions with Petrolia producers, the average pipe installation cost is estimated to be $30/metre. The actual costs would likely be much higher within the urbanized part of Petrolia where streets may have to be dug up, or lower for producers whose operations are located near a disposal well. Moreover, it is assumed that each producer would have a separate pipeline built from his location to the central facility. Total installation costs could be reduced if piping were laid so as to carry brine from more than one operator.

Pumps would be necessary at each production site to push the brine into the system. Pumps may also have to be replaced frequently because of the corrosive nature of the fluid. Based on information supplied by Petrolia producers, it is estimated that pumps could have to be replaced as often as twice annually at a cost of $1,000 per change. Total pump costs could amount to $2,000 per year per operator. There are, however, corrosion resistant pumps available. Consequently, the pump costs cited here are likely to be over-estimated.

Brine can be trucked between producer and disposal facilities using the same type of vehicles currently being used to haul oil. Harold Marcus Ltd., the company which ships all oil produced in the region to Sarnia, has four sizes of tank truck: 21 m^3, 15 m^3, 12.75 m^3 and 9.50 m^3. A 12.75 m^3 capacity truck can make a round-trip of up to 8 km in two hours, including loading and unloading, at a cost of about $40/hour. To permit operation in the winter, it would be necessary to install underground, insulated storage tanks at the production site large enough to hold a week's production of brine. Based on discussions with Petrolia producers, each m^3 of insulated storage capacity would cost $100.00 to install.

3.4 Application of the Location-Allocation Model

There are hundreds of potential combinations of facility locations and transport systems that could be devised. The location-allocation model was developed to identify the least-cost systems under different conditions. The model is a set of computer programs which determines the configuration of options which will minimize the total cost of combinations of transportation and disposal facilities.

A producer is represented as a point, or "node", and is located at the precise map co-ordinates of the brine separator and oil storage facilities currently in use. These nodes were plotted on 1:10,000 sheets produced by the Ministry of Natural Resources' Ontario Base Mapping program (sheet numbers 10 17 400 47450, 10 17 5050 47450, 10 17 4050 47450, 10 17 4000 47500 and 10 17 4050 47500).

Fourteen out of the 17 active oil producers on the Petrolia field could be located with certainty and are specified in the model.

The 14 producer locations are designated as the first 14 nodes in the model. Possible transport connections between them are limited to existing public or private roads. Heavily urbanized sections of Petrolia are excluded when possible. The junctions of this network are also designated as nodes, numbered from 15 to 34 inclusive. Road connections between the nodes are designated as "links". Because the network is fully connected, it is possible to find a path along the links to connect any pair of nodes. The nodes and pathways are shown in Figure 2.2.

The model can be used to determine the node(s) where brine from each of the producers can be disposed of at the lowest transportation cost. The model can also be used to determine which transport mode, pipeline or truck, should be used to move the brine, given the relative costs of each method and the volume of brine that must be transported.

The specific input factors or parameters that are used in the model are listed in Table 3.2. The initial or "default" set of values used in the analyses are specified in Table 3.2, as well.

A number of uncertainties and biases are associated with the various assumptions and parameter estimates that were made in order to implement the model:

(1) The installation cost of a pipeline for centralized facilities is uncertain because there is no experience in constructing such a system. It is not known whether the $30 per metre estimate used in the model is an under- or over-estimate.

(2) The cost of a separate pipeline between each oil producer and a disposal well site was estimated by the model. Some oil producers could conceivably share pipelines so that total pipeline costs are likely over-estimated.

(3) Corrosion could require more frequent pipeline replacement or maintenance. This effect would increase the per-metre costs of the pipeline.

(4) It is assumed that pumps will wear out quickly and that the operators would have to buy two new pumps per year at $2,000 per year per operator. This assumption is likely to yield an over-estimate of annual pumping costs.

TABLE 3.2

Summary of Default Values for Petrolia Oil Pool Used in the Location-Allocation Model

Symbol	Parameter Description (units)	Default Value*
	Piping option parameters:	
A	Cost of laying pipe ($/m)	30
B	Expected life of pipe (yrs.)	10
C	Pump cost ($/yr per producer)	2000
	Trucking option parameters:	
D	Holding capacity cost ($/m³)	100
E	Maximum holding period (days)	7
F	Expected life of holding capacity (yrs.)	10
G	Truck load (m³)	13
H	Time to load and unload (hrs.)	1
P	Truck speed (kph)	25
Q	Truck cost ($/hr)	37
	Disposal well parameters:	
R	Cost of completed well ($)	60,000
S	Expected Life of well (yrs.)	4
T	Capacity of well (m³/day)	300
U	Brine/oil ratio	20

* Sources of default values discussed in text.

(5) If average brine to oil ratios are actually higher than 20:1, total disposal costs could be somewhat higher because of higher trucking costs and, perhaps, the need for more disposal wells.

(6) A disposal well is assumed to last only 4 years. A simple average annual cost was calculated by dividing the total estimated capital cost (e.g. $60,000) by 4. Interest on this money is ignored for the time being. If disposal wells last longer than 4 years, the annualized facility or capital cost would be proportionately lower.

(7) Operating costs of disposal wells are negligible if the brine is transported by gravity through on-site piping (J. Gauvreau, 1985). If the operating costs of a pipeline system are found to be higher, they can be expressed by decreasing the expected life of the disposal wells (currently set at 4 years) or the pipeline system (currently at 10 years) for future model runs.

The model was used to identify and evaluate the following disposal system options:

(1) the least-cost location(s) of centralized disposal well facilities among all possible (34) sites (nodes) in the Petrolia area;

(2) the least-cost location(s) of centralized disposal well facilities among the 14 producers;

(3) centralized disposal facilities located only at existing disposal wells;

(4) require only truck transport of brine to central disposal wells; and

(5) construct disposal wells at each producer site.

A summary of the cost estimates for the five system options is presented in Table 3.3

With respect to system options (1) and (2), the location-allocation procedure located disposal wells at sites that currently have no disposal wells. Indeed, one of the lowest cost locations for a centralized disposal well is a non-producer "node". New disposal wells would, therefore, have to be installed. The total annual cost of options (1) and (2) was estimated to be essentially the same, about $140,000 per year or $1.12 per m^3 of disposed brine. Capital costs are the same in each case, $240,000.

TABLE 3.3

Comparison of Brine Disposal Facility Location and Transport Options

Option	Location of Brine Disposal Facilities	Quant. Brine Disposed at each Well (m^3/yr)	Total Capital Cost for Wells $	Costs per year				
				Facil. Costs $	Transp. Costs $	Total Cost $	\$/m^3 Brine Disposed	\$/m^3 Oil Produced in 1984*
1. Least-Cost, locate	4 Bender	21,827	120,000	30,000	17,190	47,190		
disposal wells at	23	103,064	120,000	30,000	62,429	92,429		
any of 34 Nodes		124,891	240,000	60,000	79,619	139,619	$1.12	$22.36
2. Least-Cost, locate	4 Bender	21,828	120,000	30,000	17,190	47,190		
disposal wells at	8 Edward	103,065	120,000	30,000	63,468	93,468		
existing producer sites		124,893	240,000	60,000	80,658	140,658	$1.13	$22.52
3. Locate facilities	3 Bear Creek	103,065	60,000	15,000	64,890	79,890		
at existing	9 Jacques	21,827	60,000	15,000	27,141	42,141		
disposal wells		124,892	120,000	30,000	92,031	122,031	$0.98	$19.54
4. Central disposal	8 Edward	103,065	120,000	30,000	325,145	355,145		
system using only	9 Jacques	21,828	60,000	15,000	70,682	85,682		
truck transport		124,893	180,000	45,000	395,827	440,827	$3.53	$70.59
5. Disposal well	3 Existing wells	-	-	-	-	-		
at each								
producer site	11 New wells	125,000	660,000	165,000	-	165,000	$1.32	26.42

* Based on a total (1984) oil producion of 6,245 m^3 from 14 operators in the Petrolia Pool.

For each option, at least two disposal well locations are required because total estimated brine production exceeds the expected disposal capacity of a single well. In the centralized disposal options, an additional disposal well is needed at each site as back-up. Consequently, four new wells must be installed under options 1 and 2. Furthermore, three of the producers are located in the southeast corner of Petrolia while the rest of the operators are in the north and west quadrants of the town (see Figure 2.2). Transport of brine from the three producers in the southeast to a central facility in the north and west quadrants would be more costly than would locating a central disposal well in the southeast quadrant for these producers.

The third option specifies that the location of central facilities must be chosen from among producers which already have disposal wells. Of the four producers which currently have disposal wells, Bear Creek (#3), Cartier (#7), Jacques (#9) and Canflow (#6), the Canflow site would be ineligible for centralized disposal because the Canflow wells were used for the disposal of chemical wastes before this practice was banned in the middle 1970's. Use of this well as a centralized facility could push the chemical waste materials into other wells and ultimately contaminate ground or surface waters.

A centralized disposal system which includes all three of the eligible sites (i.e. Bear Creek, Cartier and Jacques) would minimize transport costs to no more than $70,000 - $80,000 per year. However, three extra disposal wells would have to be installed at a cost of $45,000 per year or a total annual outlay of about $125,000. Reducing the centralized disposal locations to the Bear Creek (#3) and Jacques (#9) sites would increase the annual transport costs to $92,040 but reduce capital costs by $15,000 per year. The total cost for this option would, therefore, amount to $122,031 per year or 98¢ per cubic meter of brine disposed.

Since pipelines are as yet untried, trucking is the only transportation mode that is currently available. The fourth option requires that all operators have brine hauled to centralized disposal sites by truck. In order to minimize transport costs under this option, disposal wells would have to be located at the Edward and the Jacques properties. Jacques has already installed a disposal well. If two wells were to be installed at each site, three new wells would have to be constructed. The total cost of this option could amount to as much as $440,827 per year or nearly $3.53 for every m^3 of brine disposed. Total transport costs would come to $396,000 per year.

The fifth option assumes that each operator would build a disposal well on his own property. Omitting the three operators who already have disposal wells (Jacques, Canflow and Bear Creek Resources), the total capital installation cost of a "disbursed" system would amount to $660,000, or $165,000 per year based on an installed cost of $60,000 per well and a 4-year life span.

Based on the assumptions and parameter values used in this analysis, and which are listed in Table 3.2, the potentially lowest cost system to dispose of all formation fluids into disposal wells would utilize existing disposal wells and could impose as much as $122,000 in extra costs per year on the 14 operators in and around Petrolia. However, these results assume installation of a pipeline transport system which could take a year or more to install. Trucking the brine to disposal wells could begin immediately but this transport mode would cost Petrolia operators as much as $441,000 per year.

4.0 SENSITIVITY ANALYSES OF UNCERTAIN MODEL PARAMETERS

4.1 Definition of Alternative Parameter Values

Uncertainties and biases are associated with some of the model parameters. A sensitivity analysis shows how changes in different parameter values would affect the characteristics of the optimal (least-cost) brine disposal systems. The sensitivity tests involved changing the values of a single parameter or variable while leaving all others at default levels. One test was made in which several parameter values were adjusted so as to postulate extremely high-cost conditions.

Because the parameters related to piping are so uncertain, each of the three variables which determine the annual cost of a pipeline system was varied in the following ways. The cost of laying pipe (Parameter A in Table 3.2) was increased by 100% and decreased by 50% to $60 and $15 per metre respectively. The lower cost represents a system whereby producers share pipelines to a central facility and will need to install much less piping than is assumed by the model. The expected life of the pipeline (B in Table 3.2) was decreased from 10 years to 8, 6 and 4 years. A lower life (or more frequent replacement) of pipelines could result if the pipes clog up with waxes or freeze during the winter. The default value for the annual cost of a pump (C in Table 3.2), $2,000 per producer per year, is based on the assumption that 2 pumps would have to be purchased each year, a somewhat pessimistic expectation. Real annual pump costs would likely be lower so that alternative parameter values of $1,000 and $500 were used in the sensitivity tests.

If piping costs were to increase relative to trucking, some producers would find it cheaper to send brine by truck so that a larger proportion of the brine produced would be shipped by that mode. If the transport modes were to change, it is likely that the optimal central disposal site locations would be changed as well. However, if piping costs decrease relative to trucking, producers would have an incentive to send a greater proportion of brine by pipeline and it is unlikely that optimal centralized disposal well locations would differ from those for the default values.

Trucking mode parameters (D through Q in Table 3.2) are more certain since they were reported as actual costs by the trucking company that serves the Petrolia area producers. Consequently no sensitivity tests were performed with these parameters.

Disposal well cost parameters are also uncertain. As noted, the cost of completing a disposal well could be cheaper than the $60,000 default value if a producer did the work himself and employed used equipment. A well could also be more expensive if a producer had to hire someone to install a well. Consequently, alternative installation costs of $100,000 and $40,000 per well were used in the analysis. Because disposal site locations are determined by transport costs, it does not appear likely that installation costs would affect the optimal location of the centralized disposal sites. These cost changes will most certainly affect the total cost of the brine disposal system.

The expected life of a disposal well was postulated to be no more than 4 years in the default values. However, the wells will probably last much longer. An 8-year value for the expected life of the disposal well (S) was, therefore, examined. A longer life span would lower the overall cost of disposal but would not necessarily affect the optimum siting of centralized disposal facilities.

The capacity of a single brine disposal well is very uncertain but the figure used in the default values is considered to be somewhat lower than is likely. Consequently, no alternative value was tested in this exercise.

Finally, it is possible that the average brine-to-oil ratio would be higher than 20:1 while the likelihood that the average ratio would be lower is remote. Therefore, three different ratios were tested: 30:1, 40:1 and 60:1. If more brine is produced, more disposal well capacity would be needed so long as disposal rates at a given well do not change beyond the default value. Moreover, pipeline transport would be favoured since trucking costs are directly proportional to brine volume. Increases in the generation of brine from each well would not likely affect the optimal disposal well locations or the transport costs if piping were used.

The model was used to compute the following results for comparison:

- Breakpoints limits.
- Distribution of transport costs between trucking and piping.
- Least cost sites for centralized disposal wells from among 14 producer sites.

- Allocation of brine between pipeline and trucking transport modes.

- Total transportation costs per year.

4.2 Results of Sensitivity Analyses

A summary of the parameter values and the results of the sensitivity analyses is presented in Table 4.1. The most striking, and surprising, result is that nearly all changes in the parameter values would change the number and location of the optimal disposal sites. Using the default values, the Bender (#4) and the Edward (#8) sites would achieve the lowest transport costs. However, all but two of the sensitivity tests prompted a shift to the Ayrheart (#2), Cartier (#7) and Bender (#4) sites as the least-cost locations. In a number of cases, the addition of the Jacques (#9) site is indicated. The location of these sites are shown in Figure 2.2.

Under very high cost conditions where the parameter set included a pipe cost of $60/metre, the cost of a completed well of $100,000 and a brine to oil ratio of 40:1, the four sites, #2, #4, #7 and #9, were specified as optimal.

Total transportation costs would increase above the amount indicated for the default values (i.e. $80,658 per year) in only three cases: where pipe cost was increased to $60/metre, where the expected pipe life was dropped to 4 years and where the cost of a completed well was raised to $100,000. Some remarkable cost decreases occurred under a variety of changes. For example, decreases in the annual pump cost lowered the total transport cost by 37 to 42 percent. Total transport cost is also sensitive to the cost of laying pipe (A).

Based on these analyses, the factors that have the most influence on the costs of a centralized brine disposal program are the cost of laying pipe (or the total amount of pipe required), the annual cost of brine pumps (i.e. how long will they last?) and the cost of a completed disposal well. It would appear that the brine to oil ratio has a relatively small effect on transport costs although higher volumes of brine would virtually eliminate the demand for truck transport.

It would appear that sites #2, #4, #7, #9 and #8 are the least-cost sites given the cost conditions postulated in these analyses. Moreover, as cost and brine volumes increase, the amounts and proportion of brine carried by trucks steadily diminish.

TABLE 4.1

Summary of Results of Sensitivity Analyses

Parameter (Lable) = New Value*	Ship by Pipe if above: Short Distances (m^3/yr)	Ship by Pipe if above: Long Distances (m^3/yr)	Percent Transportation Costs Pipe	Percent Transportation Costs Truck	Least Cost Disposal Well Sites	Brine Volumes (000m^3) Pipe	Brine Volumes (000m^3) Truck	Transportation Costs ($000's)
1. Default Parameters**	658	26,351	74	26	4, 8	122.3	2.6	80.7
2. Pipe Cost (A) = 60	658	52,703	53	47	2, 4, 7, 9	120.1	4.8	76.3
3. Pipe Cost (A) = 15	658	13,176	87	13	4, 8	122.3	2.6	56.6
4. Exp Pipe Life (B) = 8	658	32,935	67	33	2, 4, 7	122.4	2.5	72.96
5. Exp Pipe Life (B) = 6	658	43,919	62	38	2, 4, 7, 9	122.4	2.5	69.4
6 Exp Pipe Life (B) = 4	658	65,878	47	53	2, 4, 7, 9	120.5	4.4	86.0
7. Pump Cost C = 1000	329	26,351	77	23	2, 4, 7	122.4	2.5	52.8
8. Pump Cost C = 500	165	26,351	77	23	2, 4, 7	122.4	2.5	46.8
9. Cost of Completed Well R = $100,000	658	26,351	74	26	4, 8	122.3	2.6	80.7
10. Cost of Completed Well R = $40,000	658	26,351	74	26	2, 4, 7, 9	121.8	3.1	54.6
11. Expected Life of Well S = 8	658	26,351	74	26	2, 4, 7, 9	122.3	2.6	54.6
12. Brine/Oil Ratio U = 30:1	658	26,351	82	18	2, 4, 7	183.4	3.9	69.0
13. Brine/Oil Ratio U = 40:1	658	26,351	90	10	2, 4, 7, 9	249.8	0	59.8
14. Brine/Oil Ratio U = 60:1	658	26,351	96	4	2, 4, 7	374.7	0	70.1
15. A = 60, R = $100,000, U = 40:1	658	52,703	77	23	2, 4, 7, 9	244.6	5.2	85.2

* Model runs are carried out by changing only the parameter indicated and leaving all other default values unchanged.

** See Table 3.2.

5.0 ECONOMIC IMPLICATIONS OF ALTERNATIVE BRINE DISPOSAL SYSTEMS

5.1 Financial Implications of a Disbursed System

Operators may install their own disposal wells or they may transport the brine to central facilities for disposal. These two basic approaches have different financial implications.

If producers build their own disposal wells, they will each face an installation cost of up to $60,000. As long as brine can be transported from oil wells to the disposal well by gravity, operating costs are negligible.

The installation cost can be financed from the operator's own funds or by debt. If each of the 11 operators who have not already installed disposal wells were to finance a $60,000 capital cost out of current revenues, this expense would consume between 26% and 33% of the total annual revenue for three of the operators and between 87% and 560% of the annual revenue for the remaining eight.

Direct financial impacts would be mitigated somewhat if operators borrowed the funds. The annualized capital cost used in the analyses amounted to $15,000 per year. This expenditure would consume between 6.5% and 22% of the total 1984 annual revenue of seven operators. An expenditure of $15,000 per year would still amount to over 100% of annual revenue for two operators and between 25.7% and 68.3% for the remaining five operators.

Using 1985 total revenues, a $15,000 average annual expenditure would consume less than 25% of the total revenue for 8 out of 17 operators while it would amount to over 100% for two producers. Of the remaining 7, $15,000 would account for between 27% and 82% of total revenues.

Furthermore, as shown in Table 3.3, if each producer had to install a disposal well, the average cost of 1984 oil production from the Petrolia pool would increase by $26.42 per cubic meter of oil. As of December, 1986 the price paid for Petrolia field crude oil was $125.00 per m^3.

By contrast, drilling and completing a new Devonian oil well costs about $40,000. Costs per well would be somewhat lower if several wells were installed at one time (Bailey Geological Services Ltd, 1985: 100-122).

The results of the location-allocation model assessments indicate that requiring each producer to install a disposal well, or requiring them to truck all brine to central disposal facilities, would be unnecessarily costly.

5.2 Financial Implications of Centralized Systems

The results summarized in Table 3.3 indicate that a centralized system is cheaper in the aggregate and would impose lower costs on many individual producers than would be the case if each operator installed his own well.

The analyses also suggest that it would be most cost-effective (i.e., least-cost) to establish two central disposal facilities at producers' sites who have already installed a disposal well. This result is due in part to the fact that only one new well, rather than two, would have to be constructed where disposal wells already exist.

A two-site, centralized disposal system, Option 3 in Table 3.3, would impose an extra $19.54 on Petrolia producers per cubic metre of oil produced.

In addition to transportation costs, each producer who uses a central disposal service would have to pay something to the operator of the disposal facility. The appropriate price for a service like this is the marginal or extra cost of supplying it. Since producers will pay their own transportation costs, the relevant price to be paid to operators who provide disposal services would be the extra cost of installing and operating the disposal wells, plus a "normal profit". For this exercise, a "normal profit" is defined as a 12% annual return on new capital invested.

Consequently, if central disposal facilities were established at the Bear Creek Resources and Cartier sites, the extra costs that would be used to define disposal prices would be $15,000 per year for one extra brine well plus $7,200[1] for "normal profits", for a total of $22,700[1]. The capital costs of the existing disposal wells are "sunk" costs which the operators would have incurred in any event and so are not included in this calculation.

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[1] $7,200 is 12% of a $60,000 capital investment.

Under Option 3 in Table 3.3, Bear Creek would dispose of 103,065 m^3 of brine. Thus, the minimum annual price to be charged by Bear Creek to recover incremental or "marginal" costs would be $0.22 per m^3 while Jacques' minimum charge would be $1.04 per m^3. Using these disposal charges, the cost to all of the Petrolia producers would be about $29,500 over and above the $92,031 in transport costs. The two producers who operate the central disposal wells would not incur extra disposal charges. About 62% ($18,200) of the annual disposal charge revenue would go to Bear Creek while the remainder, $11,323, would be received by Jacques. These revenues would offset the annual capital charge for the disposal wells which amount to $15,000 per year.

Charging a different disposal price at each facility may raise questions of equity. However, different prices are often charged for similar services to different customers by water, telephone or power utilities. Moreover, if oil producers opted for a different arrangement or tried to re-direct brine from, say, the Jacques to the Bear Creek facility, the extra transport costs would be much higher. In any event, the different prices reflect the different costs involved in supplying the service, not a higher profit to one of the disposal well operators.

In order to assess the impact of the costs of this disposal system on individual Petrolia producers, estimates of oil production operating costs and the resulting net revenues are required. Cost data from two large and one small oil producer are presented in Table 4.1. Assuming an average oil production of 40.29 m^3 per well per year, the apparent average cost attributable to these operators range between $89 per m^3 to $240 per m^3. These average costs may be overstated in that depreciation represents funds that are actually retained by the operator. However, the average cost per m^3 of oil reported by one of the large producers is higher than the most recent oil price, $125 per m^3.

As shown in Table 3.3, the lowest cost brine disposal option could add, on the average, an extra $19 or $20 to the cost of each m^3 of oil produced by Petrolia operators. While this may not force all producers into a loss situation, especially owner-operators who have relatively low-cost operations, the cost impacts could be problematic for some producers. However, these estimates probably overstate disposal costs to Petrolia producers as many will find it cheaper to install their own wells.

TABLE 5.1

Annual Oil Production Costs of Devonian Producers in Petrolia, Ontario

Cost Items	"Large" Producer #1 (24 wells)	"Large" Producer #2 (18 wells)	"Small" Producer (4 wells)
Direct Expenses			
Hydro	N/A	3,288	625
Labour	N/A	34,000	7,800
Depreciation	56,927	12,000	2,460*
Hardware/maintenance	N/A	24,000	1,692**
Transportation	7,865	4,095	750
Taxes	N/A	N/A	1,069
Sub-total	174,079	77,383	14,396
Administration/ supervision/financial carrying costs, etc.	58,304	12,000	***
Total Costs	$232,383	$89,383	$14,396
Cost/well	$ 9,683	$ 4,965	$ 3,599
Cost/average m^3 oil	$ 240	$ 123	$ 89

* Estimated on the basis of $11,500 @ 12% over 10 years and 1,018 @ 12% over 3 years.

** A simple average of $848 in 1984 and $2,535 in 1983.

***Operator does not charge for own time. If he did, this item would amount to an additional $6,000 to $12,000/yr.

Moreover, the uncertainties noted in Section 3.4 indicate that disposal costs might be lower than the estimates presented here. For example, brine pumps will probably last longer than one year and oil producers will likely share pipelines to centralized facilities rather than build their own from each producer site. Field work would also be needed to obtain more reliable estimates of the brine output for each producer.

Based on the foregoing analyses, operators with existing disposal wells should be a point of departure for a centralized brine disposal system. The use of existing disposal wells holds the promise of minimizing both transportation and total disposal costs for all producers. Moreover, it would permit the development of a systematic program in which the remaining uncertainties and problems associated with the program could be identified and resolved.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The water quality of the Stonehouse Drain and other area watercourses has long been impaired by the formation fluids (or "brine") from oil wells. A program of gradual reductions in Oilfield brine discharges to surface waterways is, therefore, necessary.

Based on assessments carried out by Petrolia oil producers, deep well disposal to the porous Detroit River Group is the preferred method.

A PC-based location-allocation model was designed expressly for the Petrolia Oilfield to find locations of disposal wells and transport modes that are least cost.

There are substantial uncertainties concerning the values or quantities of the various model parameters. The parameters or factors that are particularly uncertain include:

- The volume of brine production (e.g. brine/oil ratios).
- The installation cost of a pipeline for central disposal facilities.
- The useful life of disposal wells and pumps for a centralized disposal facility.

Assumptions have been made concerning each of these parameters in order to produce estimates with the location-allocation model. These assumptions have, however, tended to be conservative and probably overstate the costs for the centralized systems.

A least-cost, centralized disposal system which involve all 14 Petrolia producers would cost about $122,000 each year for transportation and installation of disposal wells. This amounts to about 9% of 1985 gross revenues for Petrolia producers. For a number of smaller producers, the annual costs of disposal could be as much or more than their total gross revenue. The extra costs could also adversely impact some of the larger producers whose production costs appear to be high in relation to prevailing prices.

Producers have no experience in organizing, operating and managing shared, centralized disposal facilities. They also have little experience or cost information about installing and operating a centralized brine pipeline system.

The cost of pipe installation, completing a disposal well or the cost and durability of brine pumps are the key variables that affect total transport costs and the optimal centralized disposal well locations.

6.2 Recommendations

Given the uncertainties associated with various aspects of the brine disposal operations, a blanket requirement that all operators construct brine disposal wells or, alternatively, undertake to have the brine trucked to central disposal wells, may create excessive hardship to some operators at this time.

Monitor the operation of existing disposal wells with a view to improving design and operating life and obtaining more accurate estimates of the relevant system parameters (e.g., installation costs, operating life of pumps, clogging of pipelines, etc.).

Establish a demonstration project to test the installation and operation of a centralized disposal facility. This project could involve existing disposal wells at Bear Creek Resources, Jacques or Cartier, together with nearby producers, particularly those which discharge into Buttermilk Creek. This project would be intended to investigate appropriate and acceptable institutional arrangements as well as the relevant technical features.

Enforce the existing requirement that brine from new oil production wells be disposed of in approved disposal facilities to prevent any further deterioration of environmental quality.

Over the longer term, a system of shared and private facilities should be evolved at minimum cost. Changes in the system should be monitored and incorporated into the location-allocation model so that periodic cost estimates of various options can be generated and relayed to new and existing producers who propose to implement acceptable brine disposal. As the necessary technology and administrative arrangements are proven, brine disposal requirements can be gradually extended to smaller producers whose brine causes less obvious problems.

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APPENDIX A

LOCATION-ALLOCATION MODEL

for

EVALUATING THE COSTS
OF BRINE WELL DISPOSAL OPTIONS

A.1 INTRODUCTION

The Location-Allocation Model used in this study is adapted from a more general formulation developed by Professor Michael Goodchild (Goodchild and Noronha, 1983).

A location-allocation model is used to determine the best or optimal location for one or more facilities from which some service is to be provided to a dispersed population. The **location** problem concerns where to locate a facility, given knowledge of whom is to be served by each facility. The **allocation** problem is to decide who should be served and from which facility. In most applications, including the present one, both problems must be solved simultaneously.

A.2 MODEL COMPONENTS

The model consists of five modules, as follows:

- SPA2. This program takes node and link data and finds the lengths of the shortest routes between all pairs of nodes. The input consists of two files, one of nodes and one of links, and the output is a file of weighted distances. The program uses a standard shortest path algorithm, and is described in detail in Goodchild and Noronha (1983). The version used is written in BASIC for the Microsoft MS DOS BASIC compiler. Both source and executable module are included;

- EDIT. This program is written in interpreted BASICA. It gives the user the facility to edit the existing parameters of the model or even create new ones. Model parameters include the costs of disposal wells and transport of brine. Fourteen parameters have been defined in the current model. The output is a file of parameters which are used in subsequent computations;

- ANAL. This program is written in interpreted BASICA. It takes a file of model parameters and allows the examination of various features of the transport cost functions of the two modes, trucking and piping. It also converts an input distance file into an output file of costs and associated transport modes;

- ALLOC. This program is a substanially modified version of the ALLOC described in Goodchild and

Noronha (1983). It is written in compiler BASIC. Its purpose is to identify an optimum arrangement of facilities in order to minimize the sum of transport and facility costs. Details of the algorithm used are given in the discussion below; and

- EVAL. This program, in interpreted BASICA, is designed so various statistics on a given arrangement of facilities, either the optimum or some other alternative arrangement, can be obtained. It has been extensively modified from a version in the Iowa monograph.

Two versions of the nodes file have been created for modelling purposes. In the file NODES.PET, all nodes in the system are considered to be candidates, or potential locations, for disposal facilities. File PRODS.PET allows disposal facilities to be located only at producer nodes. Both files have the following format:

Six numbers, integer or decimal, separated by commas:

- node identification number, 1 through 34
- region number, always 1
- volume of oil produced in m^3 in 1984;
- 1, if node is a potential facility location, else 0;
- UTM easting of node, measured from 1:10,000 sheet; and
- UTM northing.

Links data have been coded in the file LINKS.PET, using the following format:

Three numbers, integer or decimal, separated by commas:

- origin node number (either end of a link can be regarded as the origin)
- destination node number; and
- length of link in metres

The EDIT module is designed so the model's 14 input parameters, which were discussed in the body of the report, can be changed. The full list of parameters with the associated default value is summarized in Table A.1.

TABLE A.1

Summary of Default Values for Petrolia Oil Pool Used in Location-Allocation Model

Symbol	Parameter Description (units)	Default Values
Piping option parameters:		
A	Cost of laying pipe (\$/m)	30
B	Expected life of pipe (yrs.)	10
C	Pump cost (\$/yr per producer)	2000
Trucking option parameters:		
D	Holding capacity cost (\$/m^3)	100
E	Maximum holding period (days)	7
F	Expected life of holding capacity (yrs.)	10
G	Truck load (m^3)	13
H	Time to load and unload (hrs.)	1
P	Truck speed (kph)	25
Q	Truck cost (\$/hr)	37
Disposal well parameters:		
R	Cost of completed well (\$)	60,000
S	Expected Life of well (yrs.)	4
T	Capacity of well (m^3/day)	300
U	Brine/oil ratio	20

In each of the variables B, F and S, the term 'expected life' should be taken to mean either the financial amortization or depreciation period or a useful life of a facility, as appropriate, since the cost per year is computed, in each case, as capital cost divided by the 'expected life' to the nearest year.

The cost of piping for the producer is computed by using the equation:

$$C_1 = A\ DO/B + C$$

While trucking cost is determined using the equation:

$$C_2 = E\ D\ VO/(365\ F) + VO/G\ [H + DO/(1000\ P]\ Q$$

where:

DO = the length of the path between producer and disposal facility, in metres;

VO = volume of brine to be disposed of by producer each year.

Piping thus has a fixed cost (the cost of pumping), plus a component that is linearly dependent on distance, but is substantially independent of volume.

Trucking has a nonlinear dependence on both volume and distance. The result is that trucking is least-cost for small volumes while, for large volumes, piping is more cost effective. However, the volume at which the least-cost mode changes depends on distance in a complex way. It is possible to compute the "break volume" (e.g. the volume at which the least-cost mode changes from trucking to pipelines) by equating the two expressions above and solving for VO, using the equation:

$$VO = (C + A\ DO/B)\ /\ [E\ D/(365\ F) + Q\ H/G + Q\ DO/(1000\ P\ G)]$$

As distance tends to zero, break volume tends to:

$$VO = C/[E\ D/(365\ F) + Q\ H/G]$$

which, for the default values of the parameters, amounts to 658 m^3 per year. In other words, for very short distances, a producer should truck brine volumes below 658 m^3 per yr. Above this volume, a pipeline system should be installed.

The optimum break volume is asymptotic to a limit at very large distances given by the following expression:

$$VO = (A/B) / [Q/(1000\ P\ G)]$$

which is equal to 26,351 m^3/yr for the default parameter values.

It is possible to devise figures to illustrate the mathematical results. The pipe and truck cost functions, as surfaces in a space, could be defined by distance and volume axes. The break function would then be the line formed by the intersection between these two surfaces. The projection of the line into the horizontal plane would divide the plane into two domains; that in which the trucking surface is lower and that in which piping is cheaper. One might also illustrate a typical transport cost function for a given volume, with a break between one part of the cost curve showing the linear pipe cost and the other showing the nonlinear truck cost.

The strategy adopted by the ALLOC optimization program is to examine various arrangements of facilities among potential sites in a systematic search for the least-cost combination. Cost is expressed in all cases as dollars per year. It begins with an initial solution supplied by the user, which may be an intuitive guess, or may have arisen in a discussion and is a realistic possibility. The user may then select one of three algorithms to search for improved arrangements:

- Swap algorithm. This procedure systematically considers moving each of the facilities from its current location to each node which does not currently have a facility. Only one facility is moved at a time. After examining all the possible moves that can be made, the algorithm adopts that move, if any, which produces the biggest saving in transport cost. The cycle is then repeated. The method is conventionally known as a vertex substitution or a Teitz and Bart algorithm;

- Add algorithm. Since the desired number of facilities is not known at the outset in this model, and since the swap algorithm maintains a constant number of facilities, two additional algorithms have been added to increase or decrease the number. The add algorithm examines each of the nodes which does not currently have a facility and determines the one which, if given a facility, would decrease the total cost by the largest amount. For the cost to decrease, it is necessary for the saving in transport cost resulting from the additional facility to outweigh the extra facility cost;

- Drop algorithm. This procedure examines possible removals of facilities from nodes which currently have facilities.

The mode of transport is not of immediate concern in the ALLOC optimization procedure, since it is assumed that the least-cost mode will be adopted in all cases.

The EVAL module identifies the transport mode of each producer, computes total and average transportation costs for each and generates a number of other useful statistics. The solution evaluated can be an optimized solution from ALLOC or any other test scenario.

The data files which contain the model and relevant data sets are summarized in Table A.2.

When installed, the system is initiated by typing PET in response to the MS-DOS prompt. The remainder of the system is menu-driven. It is possible to define an AUTOEXEC.BAT file containing the word PET to avoid this step.